Attachment

Statement of Problem

In attempting to utilize technology originally developed for other applications to long-term space exploration applications, such as a mission to the planet Pluto, a major question mark is the ability of the technology to be extended to the required greater lifetimes, duty cycles, and environmental extremes. Miniaturized propulsion components for a space-craft attitude control cold-gas propulsion system had been developed earlier under a Pluto Fast Flyby Advanced Technology Insertion (ATI) program. [1] The objective of this study was to assess the functional performance of the components under the flight design conditions.

Scope and Methods of Approach

This program consisted of dynamic tests of individual components and cycling tests under ambient and flight design temperature conditions of the components assembled into a breadboard cold-gas propulsion test system. LabView computer systems were used to actuate and pulse the latch- and thruster-valves and to acquire the measurement results (pressure, temperature, actuation voltage, and current draw). Acceptance tests were performed on the individual components at ambient temperature and at the test conditioning temperature prior to each cycling test to assess any degradation in performance with conditioning temperature and cycling.

Summary of Important Conclusions

There appear to be no technical obstacles in miniaturizing passive propulsion components like service valves, with resultant considerable weight savings.

The miniaturization of latching type valves increases the challenge of balancing the actuating and latching forces to hold the valve armature in the last commanded position under all dynamic environmental conditions and to adequately seal under low flight design temperature conditions.

A miniaturized prototype pressure regulator demonstrated the ability to meet a narrow regulated pressure band (±5%) at low outlet pressure, 34.5 kPa (5 psig), and flow, 0.35 SLPM, conditions over a wide range of inlet pressure and conditioning temperature.

The small internal displacements in low outlet pressure/flow rate mechanical-type pressure regulators increase their susceptibility to malfunction under dynamic environmental conditions. Slight dislocations of the internal mechanisms will alter their operating performance, i.e., ability to meet the functional requirements. Electronic "bang-bang" type systems should continue to be developed as an alternative pressure regulation approach.

A robust cold-gas thruster valve-seat design has been developed that demonstrated low leakage, operating repeatability, and high operating cycle life.

Statement of Data Used to Substantiate Conclusions

Following dynamic testing of one of each set of the prototype miniaturized components, the assembled breadboard cold-gas propulsion tests system, shown schematically in Figure 1, pictorially in Figure 2, and mounted in a temperature conditioning chamber in Figure 3, was cycled a total of 60,000 times under ambient and design temperature conditions. Table 1 shows the order of the testing and Table 2 the order of the performed component acceptance tests.

The latch valve internal leakage measurement results are listed in Table 3. No measurable leakage (NML) could be detected for either latch valve before or after the first 10K ambient temperature cycles. At -20°C V2, which had been dynamically tested and unlatched at the highest (0.5 g^2/Hz) random vibration level, would not open. Raising the temperature back to 20°C allowed the valve to be opened. The second latch valve, V3, had a gross leak at -20°C which exercising the valve didn't correct. At the subsequent ambient acceptance test V2 could not be closed, and it remained in the open position for the balance of the test program. No measurable leakage was detected for V3 here and for the balance of the test series.

The internal leakage measurement results for the two cold-gas thrusters are shown in Table 4. T2, which was dynamically tested, showed no measurable leakage throughout the test series. Helium leak checks before and after yielded 3.2 x 10-9 and 2.0 x 10-8 scc/s, respectively. T1 developed a detectable leakage - 6 to 7 x 10^{-3} scc/min. GN_2, still below the prototype technical specification value of 10-2 scc/min. GN_2 - over the final 20K ambient temperature cycles.

The pull-in and drop-out voltages (Table 5), measured to ±1 V, for the two thrusters showed little or no deviation over the span of the test series.

Figure 4 shows voltage and current pulse traces for the two thruster valves - taken at the conclusion of the 60,000 cycles, but essentially unchanged throughout the series. Table 6 shows representative actuation voltage, current draw, and power values for the respective conditioning temperature cycles. The excitation voltage was held at the thruster manufacturer's acceptance test value of 23-24 volts. As shown, the current drawn by the two thrusters increased at -20°C and decreased at 70°C.

FIG. 1

ATI BREADBOARD TEST SYSTEM

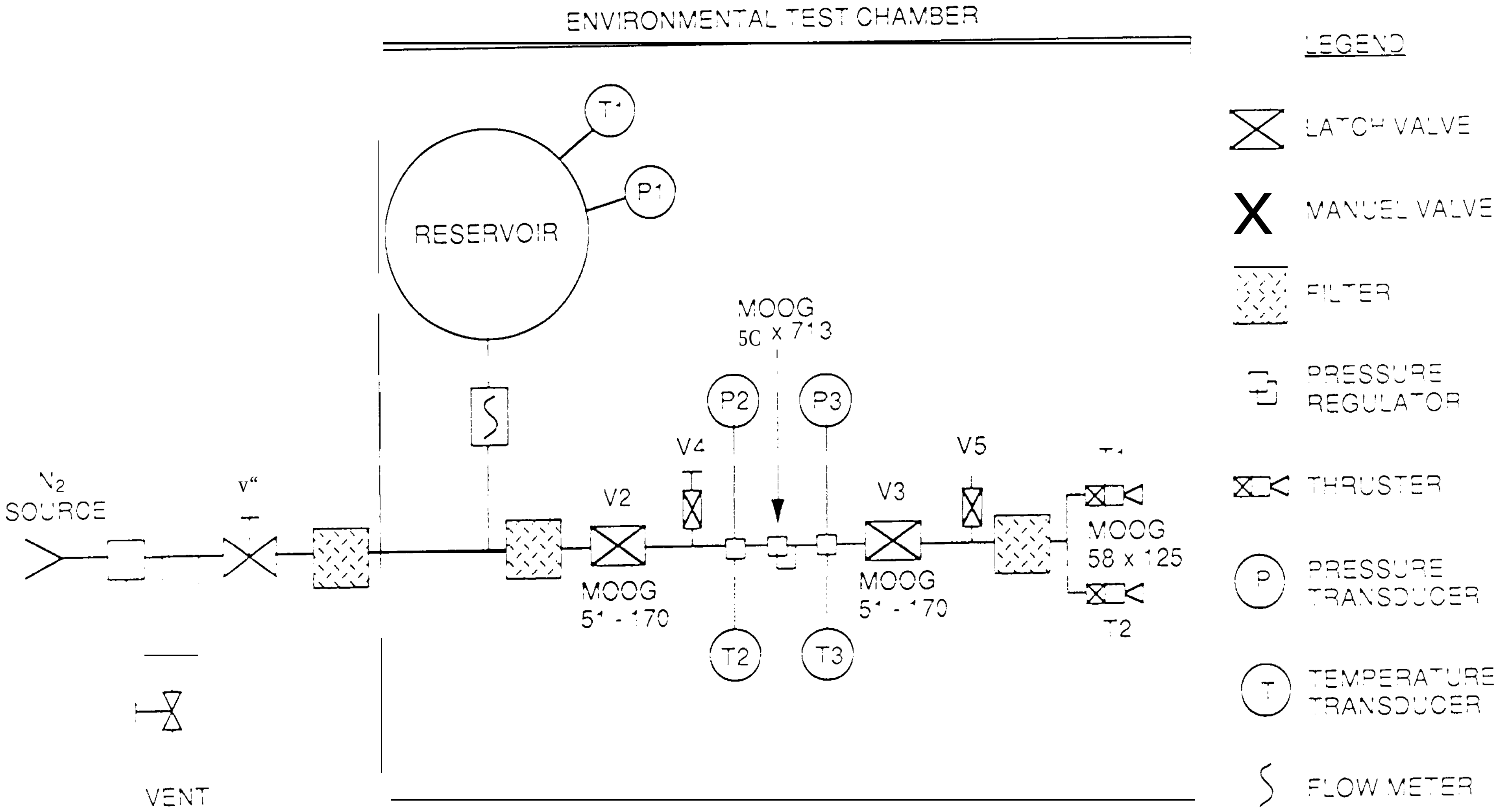
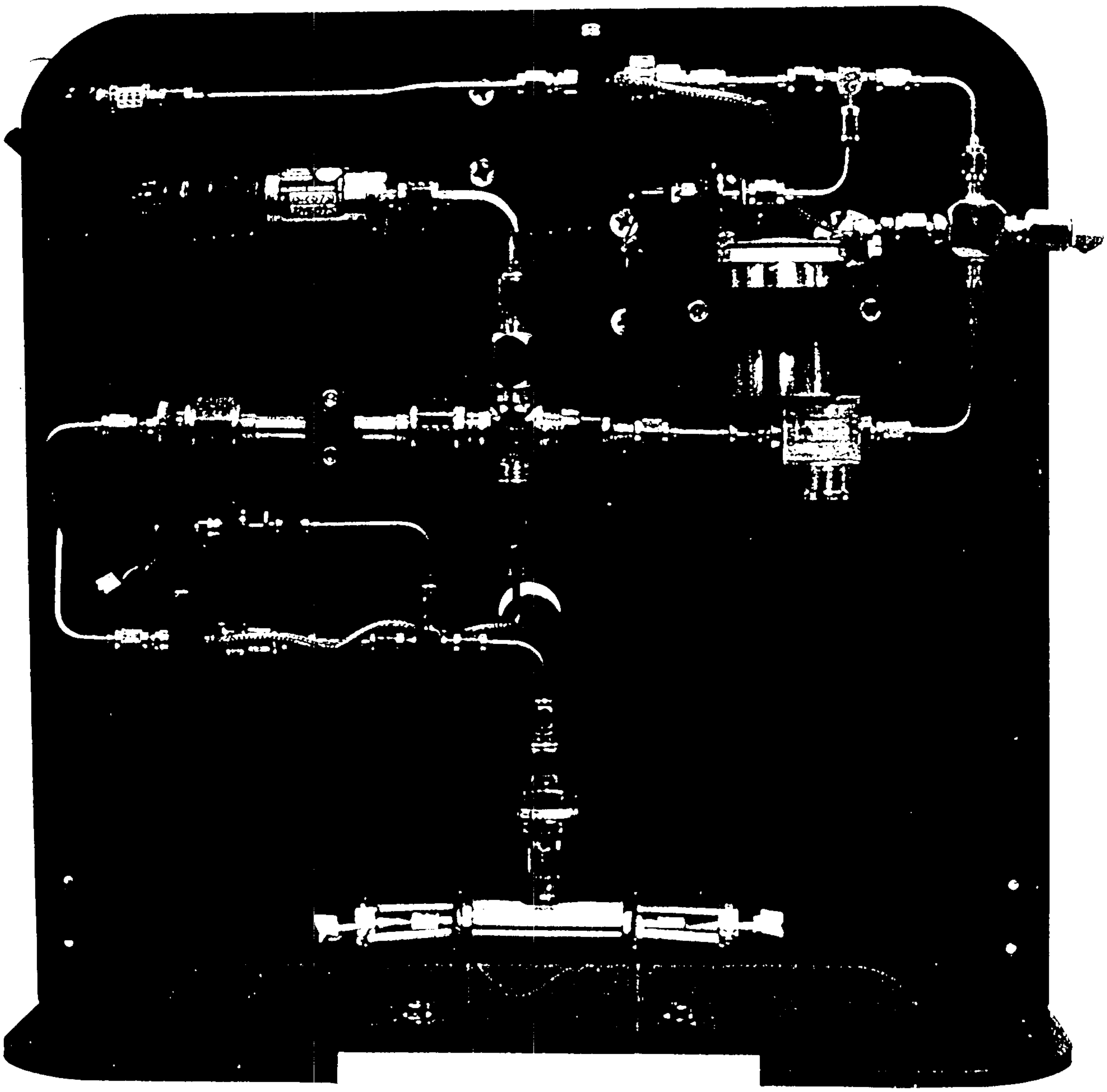


FIG. 2
BREAD BOARD COLD-GAS PROPULSION
TEST SYSTEM - FRONT VIEW



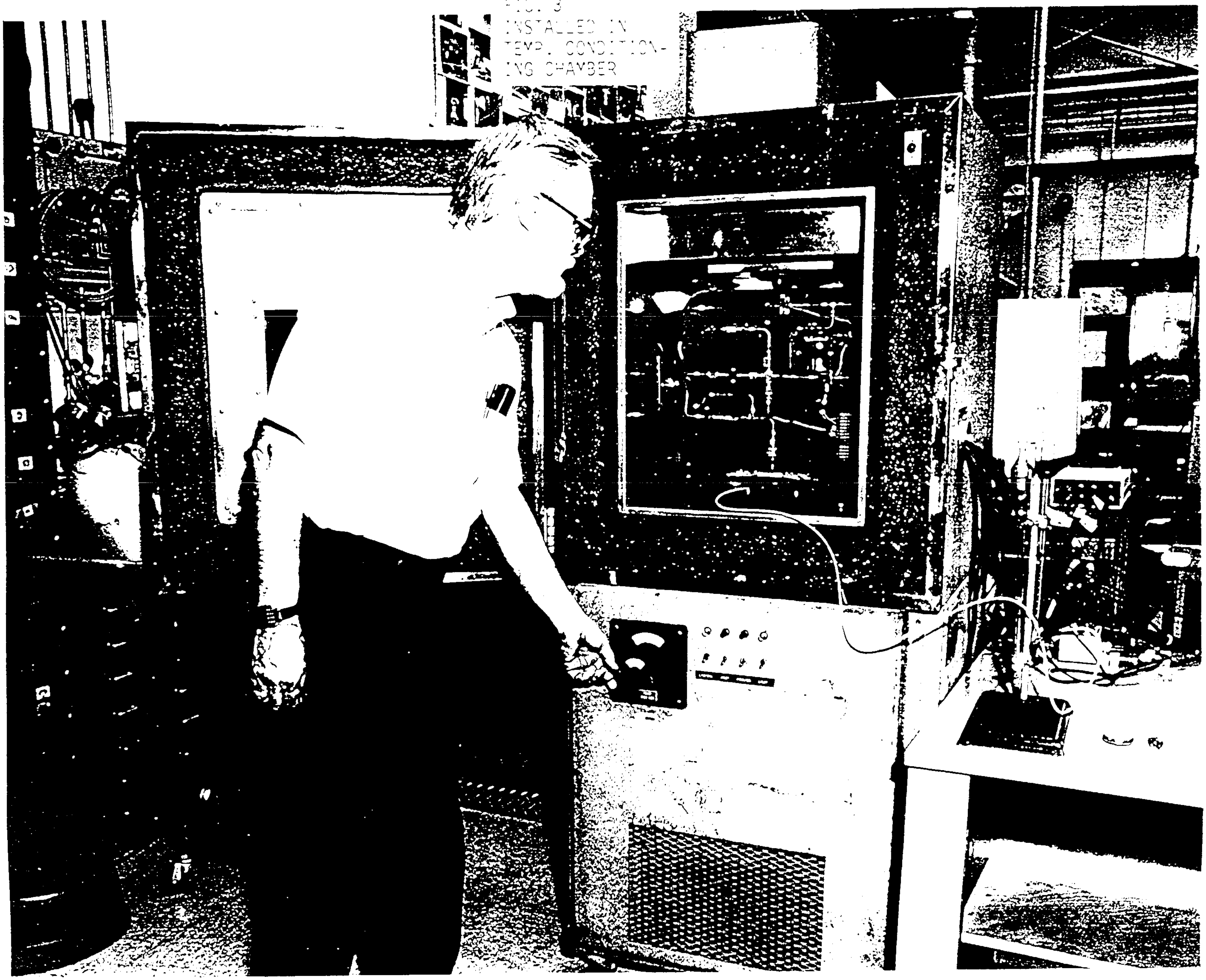


FIG. 3
INSTALLED IN
TEMP. CONDITION-
ING CHAMBER

Table 1, Testing Order

1. Ambient Temperature Test

   a. Component Acceptance Tests
   b. Thruster Cycling (10K)

2. Cold Conditioning-Temperature Test (-20°C)

   a. Component Acceptance Tests - Ambient Temperature
   b. Component Acceptance Tests - -20°C
   c. Thruster Cycling (15K)

3. Hot Conditioning-Temperature Test (70°C)

   a. Component Acceptance Tests - Ambient Temperature
   b. Component Acceptance Tests - 70°C
   c. Thruster Cycling (15K)

4. Repeat Ambient Temperature Test

   a. Component Acceptance Tests - Ambient Temperature
   b. Thruster Cycling (20K)
   c. Component Acceptance Tests - Ambient Temperature

Table 2, Order of Component Acceptance Tests

1. Measure leakage of latch valve V2 (bubble meter) over period of 10 minutes.
2. Measure leakage of latch valve V3.
3. Measure leakage of thruster T1.
4. Measure leakage of thruster T2.
5. Measure pull-in and drop-out voltage of thruster T1.
6. Measure pull-in and drop-out voltage of thruster T2.
7. Record regulator pressure leakage over period of 1/2 to 1 hour.
8. Measure regulator regulation band, with two thrusters pulsing, over inlet pressure range of 300 to 50 psi.

Table 3 Latch Valve Internal Leakage Results

Functional Requirement: 0.01 scc/min. GN_2 (max) at 2.1 MPa (300 Psi)

	Moog Acceptance	10K cycles			15K		15K	20K
	scc/min. GN_2	Amb.	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
V2 (300 Psi)	6.67×10^{-5}	NML	NML	NML (wouldn't open)	Stuck in open position	---	---	---
V3 (5 Psi)	0.0 (300 Psi)	NML	NML	Gross leak	NML	NML	NML	NML

NML - No Measurable Leakage

Table 4 Thruster Valve Internal Leakage Results

Functional Requirement: 0.01 scc/min. GN_2 (max) at 34.5 kPa (5 Psig)

	Moog Acceptance	10K cycles			15K		15K	20K
	scc/min. GN_2	Amb.	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
T1	1.0×10^{-4}	NML	NML	NML	NML	NML	NML	7.25×10^{-3} 6.0×10^{-3}
T2	7.4×10^{-5}	NML 3.2×10^{-9} scc/s He	NML	NML	NML	NML	NML	NML 2.0×10^{-8} scc/s He

NML - No Measurable Leakage

Table 5. Thruster Valve Pull-In and Drop-Out Voltages

Functional Requirements:

Pull-in; 2.0 Vdc (max) at 45°C (113°F)

Drop-out; 3 Vdc (min) at 45°C (113°F)

		Moog Acceptance						
		10K cycles		15K		10K		20K
		70°C	Amb.	-4°C	Amb.	158°C	Amb.	Amb.
T1	Pull-in, V	13.3	15 ± 1	15	15	15-16	16	15
	Drop-out, V	4.3	4	5	4-5	5	4	5
T2	Pull-in, V	14.6	15	16	16	16	16	15
	Drop-out, V	7.3	8	7	8	9	9	8-9

Table 6. Thruster Valve Actuation Power at 23-24 Vdc Excitation Voltage

Functional Requirement: 10W (max) at 28 Vdc and 20°C (68°F)

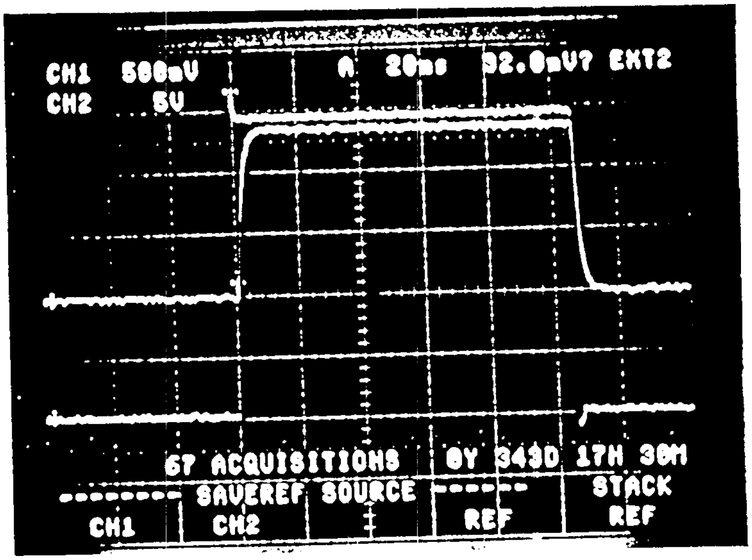
		Moog Acceptance	10K Cycles	15K	15K	20K
		70°C	Amb.	-4°F	158°F	Amb.
T1	Voltage, V	24	23	23	23	24
	Current, A	0.28	0.26	0.29	0.24	0.27
	Power, W	6.27	5.41	6.72	4.61	5.83
T2	Voltage, V	24	23	23	23	23 24
	Current, A	0.28	0.26	0.29-0,30	0.24	0.26 0.28
	Power, W	6.27	5.41	6.72 -7.?.0	4.61	5.41 6.27

FIG 4 HRUS ER VALVES VOL AGE AND CURREN PULSE RAC S

1

I (0.1 amp./div.)

V (5 volts/div.)

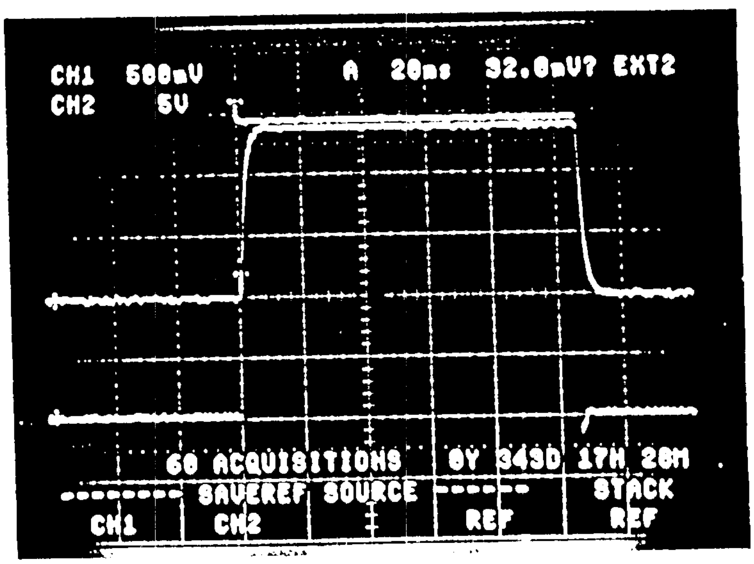


TIME (20 ms/div.)

T2

I (0.1 amp./div.)

V (5 volts/div.)



TIME (20 ms/div.)

The opening response time (lime delay from energizing to opening of thruster valve) for the two thrusters is indicated by the inflections in the high sweep-late voltage and current traces in Figure 5. These sweeps were also taken near the conclusion of the 60,000 cycles. The results for the respective conditioning temperature cycles are tabulated in Table 7, The opening response times were ≤ 1 ms throughout the test series and the final values were essentially identical to the manufacturer's acceptance test results. Valve closing response times for the latter were ≤ 250 ms.

All breadboard cycling tests were done with the non-vibrated pressure regulator in the system. Pre-test check-out of the system had revealed that the vibrated regulator would not open (remained in the lock-up position) to allow gas flow through it. The results of the pressure regulator lock-up leakage tests are. tabulated in Table 8. The initial acceptance tests showed a drop in the lock-up pressure, P3, of 0.03 psi (0.75%) over a period of 1 hr., indicating that the outlet line fittings leakage exceeded that of the regulator. The high values for the pre-70°C ambient temperature tests are probably attributable to the pressure transducer not being adequately warmed up. The lock-up pressure rose 0.3 psi, a 5.7% increase, in 15 min. at the pre-test 70°C temperature condition, indicating a definite leak. The post-70°C acceptance test at ambient temperature showed no change over 30 min. The final acceptance test showed a low 0.03 psi (0.55%) drop over a period of 2 hr.

The lock-up/regulated pressures with the two thrusters cycling, measured over a regulator supply pressure range of 300 to 50 psi, are tabulated in Table 9. The regulated pressure results, plotted in Figure 6, fell within the technical specification of 5 ± 0.3 psi. A standard deviation of ± 0.03 psi over the 250 psi range in inlet pressure was determined for the most complete data sets.

The decrease in the regulated pressure with increasing temperature is as was observed in the manufacturer's acceptance tests.

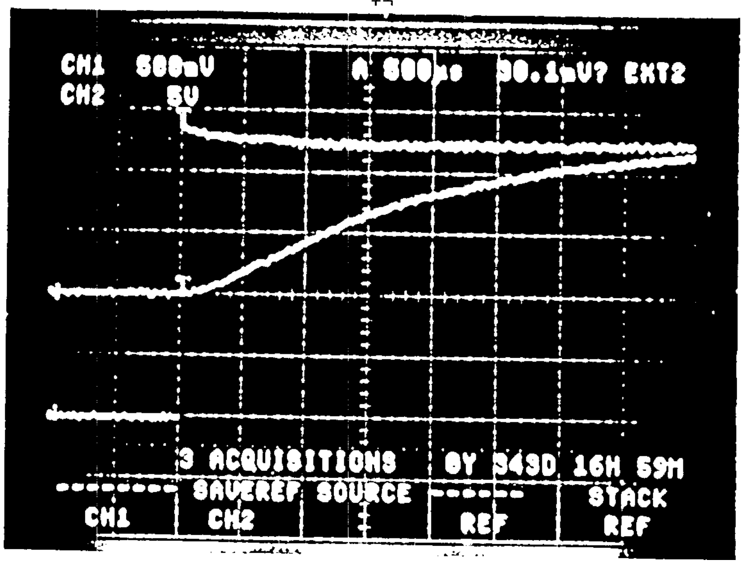
FIG. 5 THRUSTER VALVE OPINING RESPONSE TIMES

> | |< Opening Response Time (0.7 ms)

T1

I (0.1 amp./div.)

V (5 volts/div.)



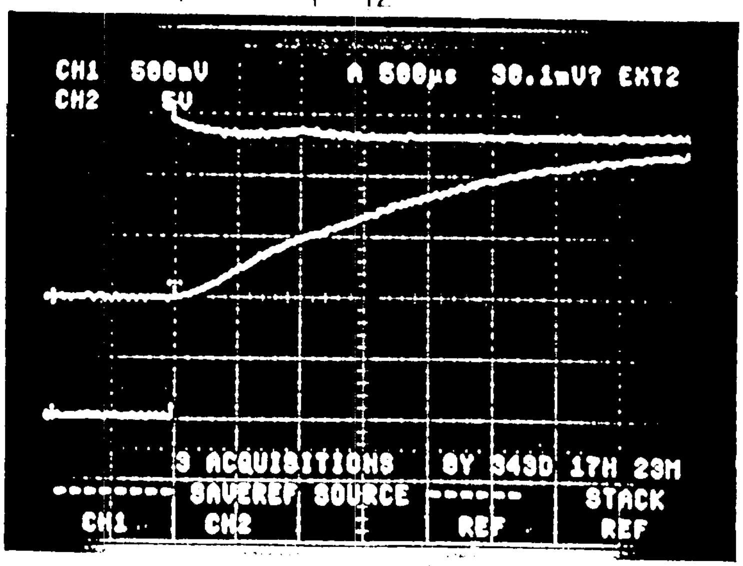
TIME (0.5 ms/div.)

→| |← (1.1 ms)

T2

I (0.1 amp./div.)

V (5 volts/div.)



TIME (0.5 ms/div.)

Table 7. Thruster Valve Opening Response ime

Functional Requirement: ≤ 2.5 ms with 24 Vdc at 45°C (113°F)

	Moog Acceptance 70°C	10 K cycles Amb.	15K -4°F	15K 158°F	20K Amb.
T1	0.66 ms	< 1	< 1	< 1	0.7
T2	1.06	~1	~1	~1	1.1

Table 8. Pressure Regulator Lock-up Leakage Test Results

Functional Requirement: 0.01 scc/min. GN_2 (max) at 2.1 MPa (300 Psi)

	P3, Psig						
	10K cles		15K		15K	20K	
Time, min.	Amb.	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
0	5.36	5.35	5.38	-7.22	5.30	5.31	5.43
7			5.37		5.46		
15	5.35	5.34	5.34	-7.20	5.59	5.31	
30	5.34			7.20		5.31	
45	5.33						
60	5.32						
120							5.40
Net Reg. Leakage	---	---	---	---	Leaking	---	---

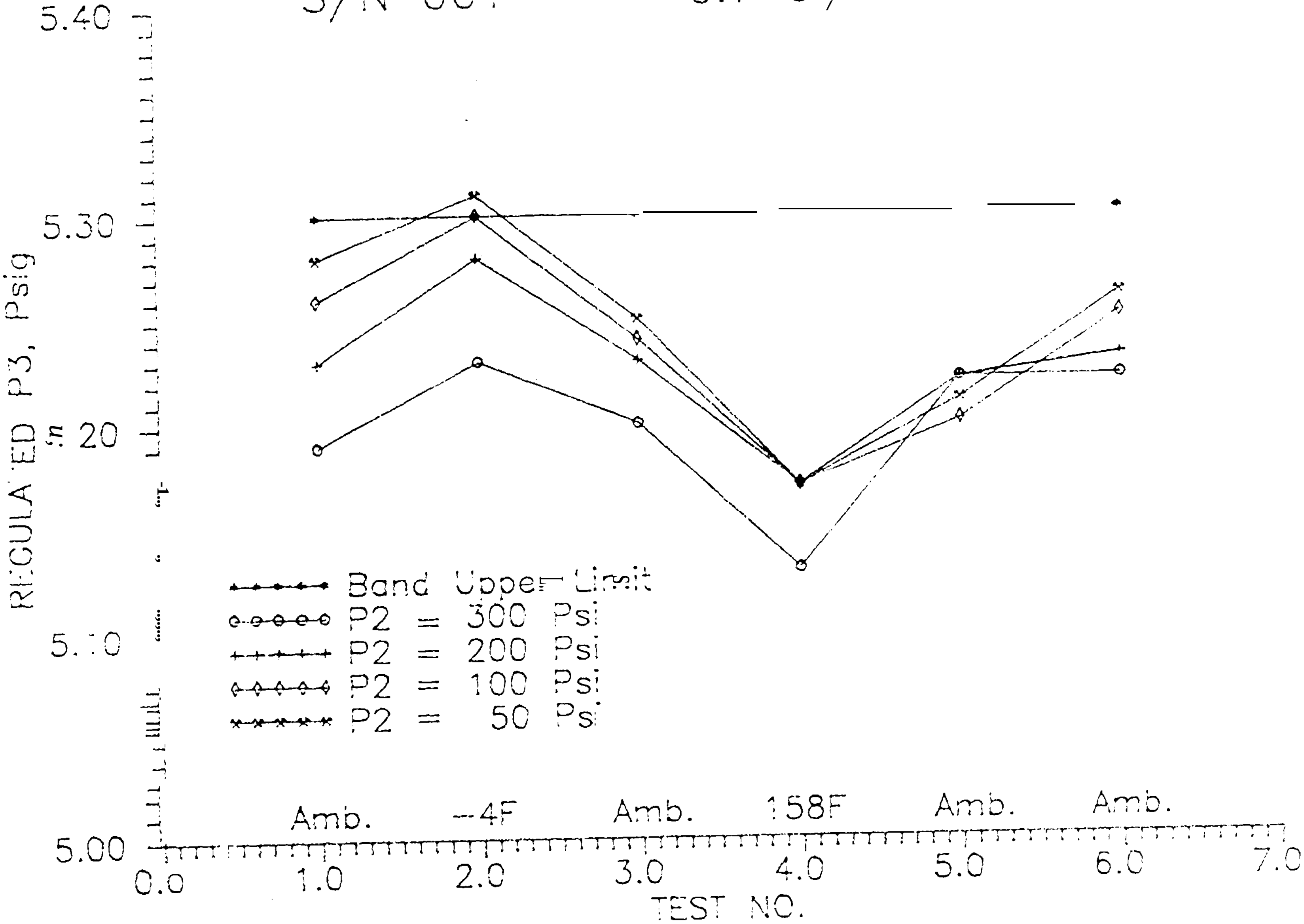
Table 9. Pressure Regulation Band Test Results
S/N 001

Functional Requirements:
Lock-up; 7 Psi (max)
Regulated; 5 ± 0.3 Psi at 1 ° sl/min.

	Lock-up/Regulated at 0.7 sl/min.					
	10 cycles		15K		15K	20K
P2, Psi	Amb.	-4°F	Amb.	158°F	Amb.	Amb.
300	5.29/5.19	5.33/5.22	5.32/5.20	5.20/5.13	5.27/5.22	5.31/5.22
250	5.31/5.21	5.38/5.26				
200	5.33/5.23	5.40/5.28	5.34/5.23	5.22/5.17	5.29/5.22	5.33/5.23
150	5.34/5.24	5.41/5.29				
100	5.35/5.26	5.41/5.30	5.35/5.24	5.23/5/17	5.31/5.20	5.35/5.25
50	5.36/5.28	5.40/5.31		5.24/5.17	5.31/5.21	5.35/5.26
Mean	5.33/5.24	5.39/5.28				
[illegible]	±0.026/±0.022	±0.021/±0.033				

FIG. 6 REGULATION BAND TEST RESULTS

S/N 001 0.7 sl/min.



Reference

1. Morash, Douglas 11. and Strand, Icon, "Miniaturized Propulsion Components for the Pluto Fast Flyby Spacecraft", AIAA Paper No. 94-3374, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 27-29, 1994.